Magnetic Insulation in a Sulfur Hexaflouride (SF$_6$) Filled Power Flow Channel

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Magnetic insulation is often used in pulse power generation and transmission systems to suppress the potentially deleterious effects of field emission due to high-electric-field stresses. The suppression is realized by applying a magnetic field orthogonal to the electric field that is extracting the electrons (field emission) from a surface. The resulting Lorentz force due to the magnetic field can cause a cycloidal motion of the electrons which can suppress the breakdown so long as the Larmor radius (the radius of the circular motion of a charged particle in the presence of a uniform magnetic field) is less than the electrode spacing. Of course, the magnetic field can be produced by the current flowing through the transmission system and/or by externally applied fields.

Often gas must be introduced in the region between the electrodes with the attendant introduction of complexity due to electron collisions with gas molecules. The collisions can be either elastic or inelastic. Further, the seemingly simple elastic collisions are complicated by the direction of the electron after the collision since the electron can gain (lose) energy by bouncing toward (away from) the anode.

Since breakdown is such an important factor in limiting pulse power system performance, it is imperative that the mechanism and mitigating methods be understood and that the database supporting the mitigating techniques is well-populated. Ionization and electrical breakdown of gases in crossed electric and magnetic fields are moderately explored areas limited to low gas pressure, low electrical/magnetic fields, and weak or non-electronegative gases primarily of interest in gas switch technology. High-power devices such as explosively-driven magnetic flux compressors operate at electrical stress, magnetic fields, and insulating (strongly electronegative) gas pressures nearly two orders of magnitude greater than published research.

The most applicable data available for SF$_6$ was taken at pressures of 22 torr, electrical fields less than 10 kV/cm and magnetic fields less than 1.3 T. However, present magnetic flux compressors may operate at a gas pressure of 760 torr (1 atm), electrical fields greater than 100 kV/cm, and magnetic fields approaching 100 T.

Figure 1 illustrates the knowledge base uncertainty that exists in the operating range of interest for LLNL's flux compression generators. It includes results of statistical analysis (Monte Carlo) of the motion of a large number of electrons and their collision products (secondary electrons, ions, and photons); the results of the Effective Reduced Electric Field (EREF) theory, which involves scaling with the gas pressure (number density); the extrapolation of earlier limited data; and five data points collected in this effort at atmospheric pressure. Unfortunately, the generation of experimental data in the laboratory has been limited by the inability to generate sufficiently high magnetic fields to demonstrate a measurable effect at atmospheric pressure.

Figure 1. Increase in the electric field required for breakdown in SF$_6$ as predicted by extrapolation of data from earlier experiments (<1.2 T and 22 torr), the EREF theory, and Monte Carlo simulation. The inset graph shows our project data at 760 torr. The operating region of interest for magnetic flux compression includes fields near 100 T and pressures near 760 torr, well beyond our database.
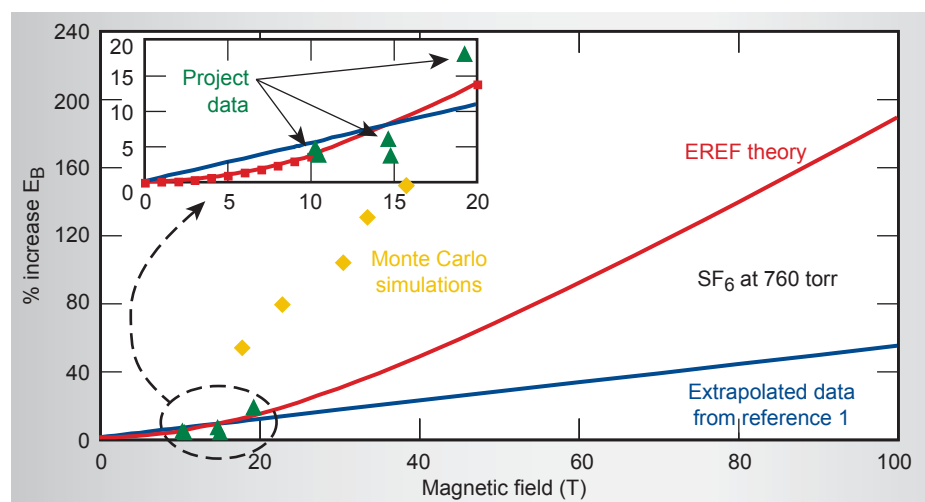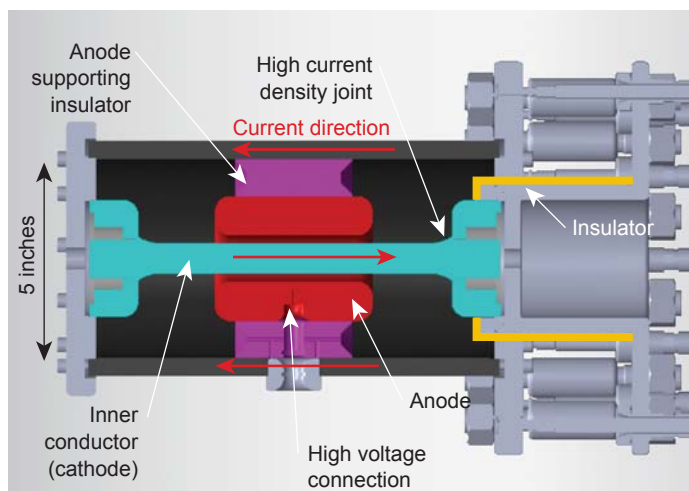
Figure 2. The coaxial load. The current is provided to the load through 12 cables, flows onto the outer conductor, and returns through the High Current Density Joint. A voltage applied to the anode with its neutral at the inner conductor generates the electric field.

Project Goals

The primary goal of the project was to populate a portion of the database by acquiring data for breakdown in SF_6 at atmospheric pressure with crossed electric and magnetic fields up to 20 T on the cathode surface. The experiments were executed in the LLNL HV Pulsed Power Laboratory using a 100-kV HV pulser, a 1-MA high-current (HC) pulser, and a coaxial load (Fig. 2).

There were two major challenges to producing the large magnetic field. The first challenge was generating a sufficiently large current to avoid the need for an extremely small cathode radius and problematic non-uniform fields. The second challenge was that the load had to withstand the tremendous magnetic pressure on conducting surfaces, pressure = $B_\theta^2 /(2\mu m)$ or 23,000 psi for 20 T.

A secondary goal was studying very-high-current-density joints. While the current from the HC pulser is introduced to the coaxial load through 12 cables, the total current is carried on the inner conductor and passes through a single joint at the end flange.

Relevance to LLNL Mission

The LLNL mission in high-energy-density physics and weapons science motivates substantial requirements for the delivery of gargantuan pulses of electrical energy to assorted loads. A critical issue in extending the performance of envisioned pulse power

devices and generators is the suppression of electrical breakdown or flashover that can exist at the extraordinarily high field stress levels that are being created. Another is the behavior of HC joints in near-yield conditions. The results of this project will indicate how far we can take the next generation of pulse power systems, and will also provide supporting evidence for validating models and theories applicable to these regimes.

FY2008 Accomplishments and Results

The experiment (Fig. 3) was executed during FY2008. Shots were done at currents (magnetic fields) between 500 kA (10 T) and 1 MA (20 T). Increases in the required electric field

stress for breakdown in SF_6 varied from 4% at 500 kA to 18% at 1 MA. These measurements (Fig. 2) support the more conservative extrapolation of data and theory over computer simulation, but indicate the need for more data in the range of interest.

Two different HC-density joints were also tested. A simple butt-joint with a diameter of 1 cm failed on a 650-kA pulse (< 200 kA/cm). A flared-end joint with a contact diameter of ~3 cm survived multiple 750-kA pulses and a 1-MA pulse (>160 kA/cm). For this we used the magnetic pressure to force the joint together during the pulse and the contact resistance for the joint actually decreased after the initial 750-kA pulse.

Related Reference

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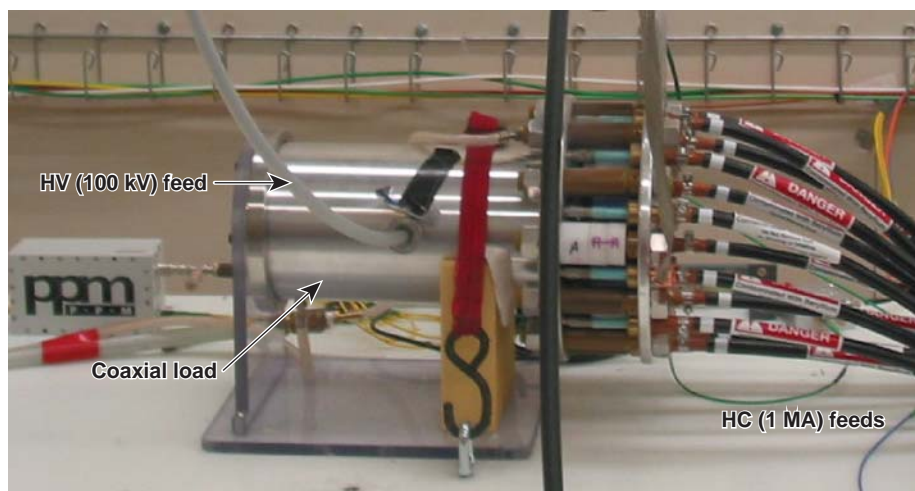
Figure 3. Photograph of the experimental configuration described in Fig. 2.